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13. ABSTRACT *(Maximum 200 words)*

Over the past three years, we investigated patterned magnetic nanostructures and their applications in ultra-high density magnetic storage. We have (1) developed nanofabrication technology and fabricated various nanoscale and high density magnetic structures; (2) demonstrated advantages of patterned magnetic nanostructures, (such as self-formation of single domain, quantized magnetization, and control of switching field by controlling the size and shape of the structures); (3) proposed and demonstrated quantum magnetic disks-- a new paradigm for magnetic storage (e.g. fabricated QMDs of 65 Gbits/in^2 density, which is nearly 100 times of the density in current commercial hard disks); and (4) developed micromagnetic modeling tool and used them to study the domain configurations and switching of patterned magnetic nanostructures, and to design and analyze nanoscale spin-valve memory elements. Our research has significantly advanced the development of future ultra-high density magnetic storage and sensors.

14. SUBJECT TERMS
magnetic nanostructures and nanofabrication, quantized magnetic disks, simulation

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Enclosure 1

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NANOSCALE ARTIFICIAL MAGNETIC STRUCTURES

FINAL REPORT

STEPHEN Y. CHOU AND JIMMY ZHU

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I. Objective

Our research has two goals: first, to explore and understand the unique properties of lithographically-patterned magnetic nanostructures and the ultimate limits of magnetic recording; and second, based on the lithographically patterned nanostructures, to develop magnetic memories that have a size much smaller and a data density much higher than that of conventional magnetic storage.

II. Summary of Major Accomplishments

2.1 Fabrication of Magnetic Nanostructures and Quantized Magnetic Disks

We developed a variety of nanofabrication techniques and used to them to fabricate magnetic nanostructures[1-4,6]. The techniques include high resolution electron beam lithography, lift-off, RIE, electroplating, sputtering, and chemical mechanical polishing. The magnetic nanostructures fabricated include (a) isolated and interactive arrays of ferromagnetic bars having a width as small as 15 nm and a density as high as 15 Gbars/in^2, (2) magnetic pillar arrays of a 35 nm pillar diameter, and 100 nm spacing, and (3) quantized magnetic disks of a 65 Gbit/in^2 density.

2.2 Study of Magnetic Nanostructures

We investigated the unique properties of patterned magnetic nanostructures (PMN) using a vibrating sample magnetometer (VSM) and a magnetic force microscope (MFM)[1-4,9]. We found: (1) as its size is comparable to magnetic domain wall size, each patterned magnetic nanostructure spontaneously magnetizes itself to form a single domain with a quantized magnetization (e.g. for a 1 μm long Ni bar of 35 nm thick, a single domain is formed when the bar width is less than 150 nm). (2) The switching field of a single domain bar increases monotonically with reduction of the bar width, reaching 3,000 Oe at 30 nm width for Co bars (60 times higher that of an unpatterned thin film) and 740 Oe at 55 nm width for Ni bars (30 times higher than that of an unpatterned thin film); and (3) unlike the bar width dependence, the switching field of the single-domain bars first increases with the bar length, but after reaching a peak it decreases. The peak switching field and the corresponding bar length are 640 Oe and 1 μm for Ni, and 1250 Oe and 2 μm for Co, respectively (the bar width is fixed at 100 nm). The non-monotonic length dependence suggests that different bar lengths have different switching mechanisms: quasi-coherent switching at the short bar length (< 1 μm) and incoherent switching at the long bar length (>2 μm).

2.3 Quantized Magnetic Disks

We proposed quantized magnetic disks (QMDs)-a new paradigm for magnetic data storage, and demonstrated several QMD embodiments[5-8]. A QMD consists of patterned, discrete, single-domain, magnetic elements uniformly embedded in a nonmagnetic disk. The elements can be bar arrays for longitudinal magnetic storage or pillar arrays for vertical magnetic storage. QMDs overcome the fundamental limits in conventional magnetic disks and therefore increase data storage density by many orders of magnitude. The most promising QMDs structure that we demonstrated is the QMD with nickel pillar arrays of a 50 nm diameter, a 120 nm height, and a 100 nm period embedded in a silicon dioxide disk. The QMDs were fabricated using e-beam lithography, RIE, electrochemical plating, and chemical-mechanical polishing. The magnetic poles of each pillar in the QMDs were clearly observed by MFM, indicating a single domain. The writing of such disks is in progress. The density of the QMDs is 65 Gbits/in^2--nearly two orders of magnitude greater than the state-of-the-art magnetic storage density.

2.4 Simulations

A. Switching of nano-scale Ni bar elements

We carried out a micromagnetic simulation study of magnetic switching behavior in nanosize nickel bars[10,13]. The switching field and switching mechanism were found to have a strong dependence on the roughness of the bar edges. By including a rough edge, the switching field of the bars was reduced as much as 40% and produced agreement with experimentally measured values.

B. Domain configurations in nano-size magnetic film elements.

Domain configurations in ferromagnetic film elements strongly depend on the shape of the elements as well as the intrinsic material properties[11]. Domain configurations in film elements of various ferromagnetic film materials, such as Co and NiFe, with various geometric shapes, such as circles and rings, were simulated.

C. Design and performance analysis of nano-size spin-valve memory elements.

We conducted a systematic micromagnetic modeling analysis on spin valve GMR memory elements[12]. It is found that for submicron size spin valve elements, edge demagnetization field, arising from the pinned layer, results in significant magnetization curling at the end edges of the free layer. This edge demagnetization phenomenon yields significant degradation of device performance. According to the modeling results, we proposed that by making the pinned film element slightly longer than the free layer so that

the ends of the free and pinned layers are separated, the edge demagnetization in the free layer can be essentially eliminated.

III. List of Publications

[1] M. S. Wei and S. Y. Chou, "Size Effects on Switching Field of Isolated and Interactive Arrays of Nanoscale Single-Domain Ni bars Fabricated Using Electron-Beam Nanolithography, *J. Appl. Phys.* **76**(10), 6679-6681, 1994.

[2] S. Y. Chou, M. S. Wei, P. R. Krauss, P. B. Fischer, "Single-domain Magnetic Pillar Array of 35 nm Diameter and 65 Gbits/in.^{2} Density for Ultrahigh Density Quantum Magnetic Storage", *J. Appl. Phys.* **76**(10), 6673-6675, 1994

[3] S. Y. Chou, M. S. Wei, P. R. Krauss, and P. B. Fischer, "Study of Nanoscale Magnetic Structures Fabricated Using Lithography and Quantum Magnetic Disk", *J. Vac. Sci. and Tech.*, **B12**(6), 3695-3698,1994.

[4] P. R. Krauss, P. B.Fischer, S. Y. Chou, "Fabrication of Single-Domain Manetic Pillar Array of 35 nm Diameter and 65 GBITS/IN^2 Density", *J. Vac. Sci. and Tech.*, **12**(6),3639-3642, 1994.

[5] S. Y. Chou, "Ultrahigh-Density Recording: Storing Data in Nanostructures," *Data Storage*, 35-40, Sept/Oct 1995.

[6] P. R. Krauss, and S. Y. Chou, "Fabrication of Planar Quantum Magnetic Disk Structure Using Electron Beam Lithography, Reactive Ion Etching, and Chemical Mechanical Polishing," *J. Vac. Sci. and Tech.*, **13**(6), 2850-2852, 1995.

[7] S.Y. Chou, P. R. Krauss and L. Kong, "Nanolithographically Defined Magnetic Structures and Quantum Magnetic Disk (Invited)" *J. Appl. Phys.* **79**(8) 15 April 1996.

[8] S.Y. Chou and P.R. Krauss, "Quantum Magnetic Disk, "*J. of Magnetism and Magnetic Materials*, **155**, 151-153, 1996.

[9] L. Kong, and S. Y. Chou, "Effects of Bar Length on Switching Field of Nanoscale Nickel and Cobalt Bars Fabricated Using Lithography," *J. of Appl. Physics*, 80(9), pp. 5205-5208, 1996.

[10] J. Gadbois and J.-G. Zhu,"Effect of Edge Roughness in Nano-Scale Magnetic Bar Switching," IEEE Trans. Magn., Vol.31, p.3209, (1995)

[11] J.-G. Zhu, "Micromagnetic Modeling: Theory and Applications in Magnetic Thin Films," MRS Bulletiin, Vol.XX, No.10, (1995).

[12] Y. Zheng and J.-G. Zhu, "Micromagnetics of Spin Valve Memory Cells," IEEE Trans. Magn., Vol. 33. (1996)

[13] Y. Zheng and J.-G. Zhu, "Intrinsic Switching Field Variation of Submicron Patterned Thin Film Elements," to be published in J. of Appl. Phys., (1997)

IV. List of Personnel Participating The Scientific Project

Principal Investigator: Professor Stephen Chou

Co- Investigator: Professor Jimmy Zhu

Post-doctoral: Linshu Kong

Graduate Students: Peter Krauss, Rick Shi, and Jason Gadbois

V. Advanced Degrees Awarded to Personnel on the Project

M.S. Degree:

P. Krauss (MSEE 1995)

Jason Gadbois (MSEE 1996)

VI. Invention Disclosure

U.S. Patent Application: "Quantum Magnetic Disk" May, 1995.

Size effects on switching field of isolated and interactive arrays of nanoscale single-domain Ni bars fabricated using electron-beam nanolithography

Ref -1

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Isolated nanoscale Ni bars with a length of 1 μm, a width from 15 to 300 nm, and interactive bar arrays with a spacing from 200 to 600 nm were fabricated using electron-beam lithography and were studied using magnetic force microscopy. The study showed that the virgin magnetic state of bars with a width smaller than 150 nm was single domain and otherwise multidomain. It also showed that the switching field of isolated bars initially increases with decreasing bar width, then reaches a maximum switching field of 740 Oe at a width of 55 nm, and afterwards decreases with further bar width reduction. Furthermore, it was found that the switching field of the interactive bars decreases almost linearly with reduction of the spacing between the bars.

I. INTRODUCTION

Understanding the behavior of a single domain magnetic particle and the interaction between the particles is very important, because these particles are the basic constituents of many magnetic recording materials. However, previously most experimental studies of magnetic particles were made in an ensemble of such particles and the properties of a single particle were inferred only through extrapolation. Due to large variation in particle dimensions, randomness of magnetization and unavoidable interaction, detailed information about single particles and their interaction is smeared out.

Due to advance in nanofabrication technology, now it is possible to nanoscale magnetic particle arrays with precise sizes, shapes, and spacing. This opens up new opportunities to understand the fundamentals of micromagnetics and develop new magnetic materials. Recently, the first reported study of nanoscale permalloy bars fabricated using electron beam lithography was carried out by a joint team from the University of California at San Diego and IBM.[1,2] In that study, isolated bars had a fixed length of 1 μm and a fixed width of 133 nm and interactive bar arrays had a fixed spacing with the strongest coupling along the bars' long axis.

In this article, we present the fabrication and investigation of isolated Ni bars with a width varying from 15 to 300 nm and interactive Ni bar arrays with a spacing varying from 200 to 600 nm with the strongest coupling in the bars' short axis. Furthermore, we report and discuss the effects of bar width and spacing on the switching field of these isolated and interactive bars.

II. FABRICATION OF NANOMAGNETIC BAR ARRAYS

The isolated and interactive nanomagnetic nickel bars were fabricated using electron-beam nanolithography and a lift off process. In the fabrication, a resist, polymethyl methacralate (PMMA), was first spun onto a silicon substrate. A high resolution electron beam lithography system with a beam diameter of 4 nm was used to expose bar arrays in the PMMA. The exposed PMMA was developed in a cellosolve and methanol solution to form a resist template on the substrate. A nickel film, 35 nm thick, was evaporated onto the entire sample. In the lift off, the sample was submersed in acetone which dissolved the PMMA template and lifted off the nickel on its surface, but not the nickel on the substrate. After fabrication, bar widths were determined using a scanning electron microscope (SEM) and the bar width presented here is the measured bar width.

For isolated bars, the bar length was fixed at 1 μm, but the bar width varied from 15 to 300 nm. The spacing between isolated bars is 10 μm. Figure 1 shows a scanning electron micrograph of a Ni bar with a 15 nm width.

For interactive bar arrays, the bar width and length were fixed at 100 nm and 1 μm, respectively. The spacing between bars along the long axis is 2 μm, but the spacing between the bars along the short axis varies from 200 to 600 nm. Therefore the interaction between bars is primarily along the short axis, and the bar arrays can be regarded as isolated rows of one dimensional interactive arrays. This is very different from that in Ref. 1 where the bars were coupled primarily along the long axis. To illustrate the fabrication resolution

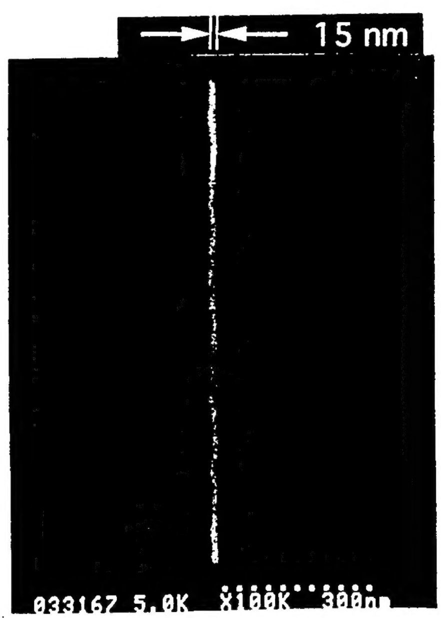

FIG. 1. SEM image of a high aspect ratio isolated Ni bar that is 1 μm long and 15 nm wide.

 0021-8979/94/76(10)/6679/3/$6.00 © 1994 American Institute of Physics

Ref-2

Single-domain magnetic pillar array of 35 nm diameter and 65 Gbits/in.^{2} density for ultrahigh density quantum magnetic storage

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Using electron beam nanolithography and electroplating, arrays of Ni pillars on silicon that have a uniform diameter of 35 nm, a height of 120 nm, and a period of 100 nm were fabricated. The density of the pillar arrays is 65 Gbits/in.^{2}—over two orders of magnitude greater than the state-of-the-art magnetic storage density. Because of their nanoscale size, shape anisotropy, and separation from each other, each Ni pillar is single domain with only two quantized perpendicular magnetization states: up and down. Each pillar can be used to store one bit of information, therefore such nanomagnetic pillar array storage offers a rather different paradigm than the conventional storage method. A quantum magnetic disk scheme that is based on uniformly embedding single-domain magnetic structures in a nonmagnetic disk is proposed.

I. INTRODUCTION

Perpendicular magnetic recording media have been considered by many as the media that will offer the largest storage density. Previously, several perpendicular recording media were developed and investigated. These include Co-Cr thin films with vertical grains,[1,2] barium ferrite powder with a perpendicular *c* axis,[3] and vertical ferromagnetic pillars plated through porous Al films[4] or plastics films with nuclear radiated tracks.[5] In all these media, the diameter of magnetic grains and the magnetization direction have a broad continuous distribution; the spacing between the grains varies and is uncontrollable; and each bit of information is stored over at least several magnetic grains.

In order to explore the ultimate size of a magnetic bit and the ultimate spacing between neighboring magnetic bits (therefore storage density), to improve understanding of the fundamental magnetics, and to develop new magnetic devices of high speed and high density, we have fabricated ultrahigh density arrays of single-domain nickel pillars using electron beam nanolithography and electroplating. The unique advantage of nanolithography is that the dimension of each pillar as well as the spacing between the pillars can be well controlled and uniform. Due to small size and shape anisotropy, each pillar is a single domain with magnetization perpendicular to the substrate. Moreover, each magnetic pillar can be used to store one bit of information. In this article we will discuss the fabrication process, magnetic force microscope (MFM) measurements, and the possibilities of a novel new recording paradigm offered by these pillars.

II. FABRICATION OF MAGNETIC PILLAR ARRAYS

A schematic of our fabrication process is shown in Fig. 1. A thin gold plating base was deposited on a silicon substrate. A high resolution electron beam resist, polymethyl methacrylate (PMMA), was then spun onto the substrate. Depending upon the desired pillar height, the thickness of the PMMA is typically 130 nm; however, 720 nm thick PMMA was also used in some cases. Dot arrays with diameters from 35 to 40 nm and spacings from 50 to 1000 nm were exposed in the PMMA using a high resolution electron beam lithography system with a beam diameter of 4 nm. The exposed PMMA was then developed in a cellosolve and methanol solution creating a template for the electroplating process. The sample was immersed in a nickel sulfamate type plating bath and nickel was electroplated into the template openings until the nickel thickness was near the template thickness. The plating rate, which is a function of plating current, template diameter, and template thickness, was well calibrated and was fixed at 45 nm/min for our work. After electroplating, the PMMA template was removed.

After fabrication, the pillars were examined using a scanning electron microscope (SEM) to verify the pillar dimensions. The resulting nickel pillars are uniform and have desired shape anisotropy. Figure 2 shows a SEM micrograph of a pillar array having a diameter of 35 nm, a height of 120 nm, and therefore an aspect ratio of 3.4. The pillar array has a period of 100 nm, and thus has a magnetic storage density of 65 Gbits/in.^{2} which is two orders of magnitude higher than the state-of-the-art storage. The pillars have a cylindrical shape with very smooth sidewalls.

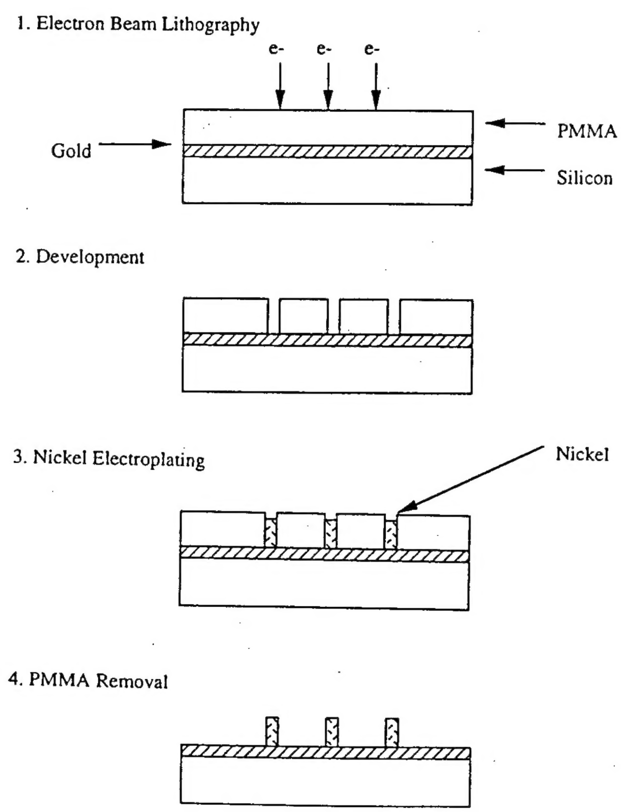

FIG. 1. Schematic of nanomagnetic pillar array fabrication process.

Study of nanoscale magnetic structures fabricated using electron-beam lithography and quantum magnetic disk

Ref-3

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(Received 22 June 1994; accepted 31 August 1994)

Two types of nanoscale single-domain magnetic structures were fabricated using e-beam nanolithography and were studied using magnetic force microscopy. The first structure is the isolated and interactive arrays of Ni bars on silicon that are 35 nm thick, 1 μm long, and have widths ranging from 15 to 200 nm and spacings ranging from 200 to 600 nm. The second structure is an array of Ni pillars on silicon that have a uniform diameter of 35 nm, a height of 120 nm, and a density of 65 Gbits/in^2—over two orders of magnitude greater than the state-of-the-art magnetic storage density. It was found that the magnetic properties of these structures can be controlled by engineering their size and spacing. When the bar width is smaller than 150 nm, the bars become single magnetic domain. As the width of the isolated bars decreased from 200 to 55 nm, the magnetic field needed to switch the magnetization of these bars increased monotonically from 100 to 740 Oe which is the highest field reported for Ni. However, further reduction of bar width led the switching field to decrease due to thermal effect. Furthermore, it was found that as the bar spacings become smaller, the interaction between the bars will reduce the switching field. Finally, based on the artificially patterned single-domain magnetic structures, we propose a new paradigm for ultra-high-density magnetic recording media: quantum magnetic disk.

I. INTRODUCTION

Coercivity, coercive squareness, and many other magnetic properties of a magnetic thin film strongly depend upon the geometric factors of the magnetic grains in the film such as the grain size and anisotropy, the grain magnetization orientation, and the spacing between the grains. Generally, however, in a conventional as-deposited magnetic film the magnetic grains have a broad distribution of the grain size, anisotropy, spacing, and nearly random magnetization. Therefore the conventional magnetic media have a large variation of local magnetic properties, making them unsuitable for ultra-high-density recording and hard to compare with theory. To develop new materials for ultrahigh magnetic recording and to obtain a better understanding of magnetic behavior of a material, many methods have been attempted in order to control the geometric factors of magnetic grains in a thin film. The approaches include control of film deposition conditions, alloying, epitaxial growth on crystal substrates, introduction of stacking faults, and insertion of nonmagnetic material between the magnetic grains. However, none of these approaches offers precise control of the geometric factors.

As nanofabrication technology advances, it is now possible to precisely control the geometrical factors of magnetic grains in a thin film using nanolithography. These nanolithographically defined magnetic materials open up new opportunities to engineer novel magnetic materials and understand the fundamentals of magnetics. Recently, a joint team from the University of California at San Diego and IBM studied nanoscale permalloy bars fabricated using electron-beam lithography.[1,2] In that study, isolated bars had a fixed length of 1 μm and a fixed width of 133 nm; interactive bar arrays had a fixed spacing with the strongest coupling along the bars' long axis.

In this article, we present the investigation of isolated Ni bars with a width varying from 15 to 200 nm, and interactive Ni bar arrays with a spacing varying from 200 to 600 nm with the strongest coupling in the bars' short axis. We will report the effects of bar width and spacing on the switching field of these isolated and interactive bars. We will also report the study of arrays of Ni pillars that have a uniform diameter of 35 nm, a height of 120 nm, and a density of 65 Gbits/in.^{2}—over two orders of magnitude greater than the state-of-the-art magnetic storage density. Furthermore, we will discuss a new paradigm for ultra-high-density magnetic recording based on the lithographically defined nanomagnetic structures.

II. ULTRA-HIGH-DENSITY NANOMAGNETIC BAR ARRAYS AND PILLAR ARRAYS

The isolated and interactive nanomagnetic nickel bars were fabricated using electron-beam nanolithography and a lift-off process.[3] All the bars are 35 nm thick. For isolated bars, the bar length was fixed at 1 μm, the spacing between bars was 10 μm, but the bar width varied from 15 to 200 nm. Figure 1 shows a scanning electron micrograph of a Ni bar with a 15 nm width and an average edge variation of 4 nm. For interactive bar arrays, the bar width and length were fixed at 100 nm and 1 μm, respectively. The spacing between bars along the long axis was 2 μm, but the spacing between the bars along the short axis varied from 200 to 600 nm. Therefore the interaction between bars is primarily along the short axis, and the bar arrays can be regarded as isolated rows of one-dimensional interactive arrays. This is very different from that in Ref. 1 where the bars were coupled primarily along the long axis. To illustrate the fabrication precision and uniformity, Fig. 2 shows a large array of Ni bars

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Fabrication of single-domain magnetic pillar array of 35 nm diameter and 65 Gbits/in.^{2} density

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Ref-4

(Received 20 June 1994; accepted 31 August 1994)

Using electron beam nanolithography and electroplating, arrays of Ni pillars on silicon have been fabricated. The effects of plating current and feature size on the plating rate were investigated. The pillar arrays have a period of 100 nm and the pillar diameters are uniform and as small as 35 nm. Because of their nanoscale size, shape anisotropy, and separation from each other, each Ni pillar is single domain with only two quantized perpendicular magnetization states: up and down. If each pillar were to represent one bit of information, the density of the pillar arrays would be 65 Gbits/in.^{2}—over two orders of magnitude greater than the state-of-the-art magnetic storage density. The ultrahigh density, together with the single-domain formation, make these pillar arrays very attractive for high-density magnetic storage devices and fundamental magnetics studies.

I. INTRODUCTION

To explore new high-density magnetic storage media and improve our understanding of magnetics, new fabrication techniques for producing closely packed nanoscale magnetic structures are required. The highest packing density is achieved when the magnetic structures are oriented perpendicular to the substrate and thus form a perpendicular magnetic recording media. Previously, several perpendicular recording media were developed and investigated. These include Co–Cr thin films with vertical grains,[1,2] barium ferrite powder with a perpendicular z axis,[3] and vertical ferromagnetic pillars plated through porous Al films[4] or plastics films with nuclear radiated tracks.[5] In all these media, the diameter and magnetization direction of the magnetic grains have a broad continuous distribution; the spacing between the grains varies and is uncontrollable; and each bit is stored over at least several magnetic grains.

In this article, we report the development of a process for fabricating ultrahigh-density arrays of single-domain magnetic pillars for perpendicular magnetic recording media using electron beam nanolithography and electroplating of nickel, a ferromagnetic material. Due to its nanoscale size and shape anisotropy, each pillar is a single domain with magnetization perpendicular to the substrate. We will discuss the factors that are important to the plating of nanoscale pillars such as plating current and feature size.

II. FABRICATION OF MAGNETIC PILLAR ARRAYS

Our fabrication process involves electron beam lithography and electroplating. The reason for using plating is that the popular lift off process cannot be used for high aspect ratio vertical structures. In the lift off process, gradual accumulation of materials at the orifice of each resist template opening during the deposition will eventually close the opening; as a result, the maximum pillar height is about the size of the template opening and large shape anisotropy is difficult to achieve.

A schematic of the process is shown in Fig. 1. A plating base of 10 nm chrome and 50 nm gold was evaporated on a silicon substrate. A high resolution electron beam resist, polymethyl methacrylate (PMMA), of 950 K molecular weight was then spun onto the substrate. The thickness of the PMMA was either 130 or 720 nm depending upon the desired pillar height. Dot arrays with diameters from 35 to 75 nm and spacings from 50 to 1000 nm were exposed in the PMMA using a high resolution electron beam lithography system that has a beam diameter of 4 nm and an accelerating voltage of 35 kV. The electron beam lithography system is a converted scanning electron microscope (SEM) and has been reported elsewhere.[6] The exposed PMMA was then developed in a cellosolve and methanol solution creating a template for the electroplating process.

The nickel plating process used a nickel sulfamate type plating bath. Such type of plating bath is known to produce films with low internal stress as compared to other types of nickel plating baths such as Watts, all chloride, or sulfate.[7] Low stress deposits are required to fabricate ultrahigh-density arrays of nanomagnetic pillars that have high aspect ratios. The nickel sulfamate plating bath consists of 367 g/ℓ nickel sulfamate $[Ni(SO_3NH_2)_2 \cdot 2H_2O]$ and 30 g/ℓ boric acid in water yielding a pH of 4. The bath was heated to 50 °C and mechanically agitated at a stirring speed of 100 rpm. The optimum stirring speed for micron scale features was found to be between 100 and 125 rpm. Stirring speeds lower than this resulted in only shallow filling of the template features and speeds higher than this resulted in rough film surfaces. During the plating, the plating current was kept constant by using a current source. The stress in the deposited nickel was tested by plating 0.5 μm thick nickel squares with an area of 25 μm^2. No cracking of the film was observed, except slight bowing at the edges, indicating that the stress was low. After electroplating, the PMMA template was removed in an oxygen ashing process leaving the nanomagnetic pillar arrays.

The nickel plating rate was found to be related to the plating current, the feature size, and the total plating area. The effect of plating current on the plating rate of nanoscale pillars with 720 nm PMMA is shown in Fig. 2. As expected, the plating rate generally increases linearly with plating current. However, at low plating current the plating rate is not a linear function of the current.

The nickel plating rate also depends upon the size of the

Cover Article

Ultrahigh-density recording: Storing data in nanostructures

Ref-5

Stephen Chou, University of Minnesota

Electronic storage densities are increasing exponentially. Commercial hard disk drives already boast of storage capacities in the vicinity of 300 Mbit/in^2, while in the laboratory, IBM has recently achieved a density of 3 Gbit/in^2. It is now apparent that further increases in storage densities are limited primarily by the nature of the recording media. A new paradigm is proposed here for achieving ultrahigh recording densities in which discrete, magnetic elements, embedded in a nonmagnetic disk by an electron beam, replace continuous, thin-film magnetic media [1]. The name given to this new recording medium is the "quantum magnetic disk" (QMD).

One of the striking properties of the discrete, single-domain element is that, in the absence of an applied magnetic field, each element magnetizes itself, and its magnetization has only two possible states: equal but opposite magnetic moments (i.e., north or south). Each of these magnetic elements can store a bit of binary information. Another striking property is that the magnetic field needed for switching the magnetization direction can be controlled through the element's geometry.

Other advantages of the QMD recording concept include a greatly simplified writing process, individual tracking, low noise (crosstalk), high thermal stability, and ultrahigh density. QMD provides the perfect counterpoint to many of the problems associated with conventional magnetic recording. To date, a storage density of 65 Gbit/in^2—over two orders of magnitude greater than the density claimed for thin-film media—has been demonstrated with the QMD recording media [2,3]. The fabrication technology used to make the QMD is similar to that used to make integrated circuits. Finally, a low-cost method for mass producing these disks, called "nanoimprinting," has been demonstrated in the laboratory [3,4].

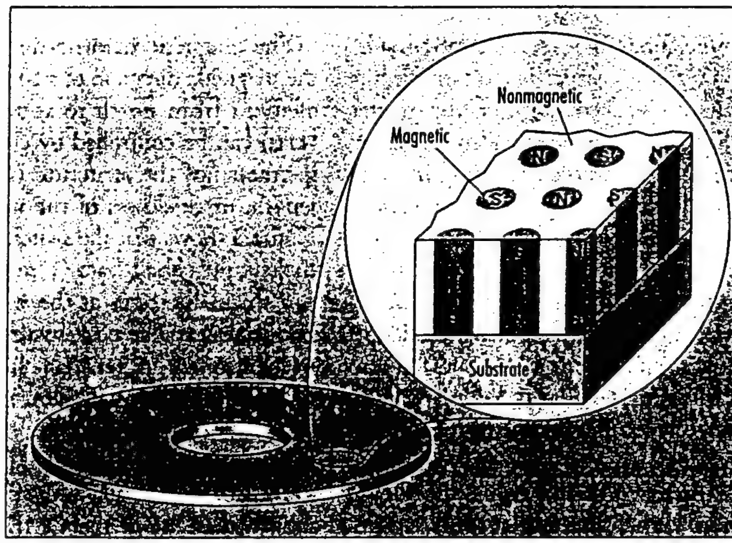

Figure 1. Schematic of a quantum magnetic disk. Prefabricated, discrete, single-domain magnetic elements are embedded in a nonmagnetic material. Only perpendicular magnetization is shown, but the disk can also be made offering longitudinal magnetization.

A NEW RECORDING PARADIGM IS PROPOSED IN WHICH MAGNETIC ELEMENTS EMBEDDED IN A NONMAGNETIC DISK REPLACE THIN-FILM MEDIA.

The advantages that QMD offers can be better appreciated if we first look at some of the hurdles that must be overcome in achieving high storage densities with conventional magnetic disks, where data is stored on a continuous, thin film of magnetic recording media supported by a rigid, nonmagnetic substrate. The thin, magnetic film consists of many, randomly oriented, polycrystalline grains. An applied magnetic field aligns a tiny patch of these grains, allowing data to be stored in the thin film. The magnetic moment, size, and location of this area represent a single bit of binary data.

Because the magnetic moments of the grains are randomly aligned in the thin film, the write heads must be very precise in defining the magnetic moment and location of each bit of data recorded on the thin film. A slight error in writing one bit can

Fabrication of planar quantum magnetic disk structure using electron beam lithography, reactive ion etching, and chemical mechanical polishing

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Ref-6

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A planar quantum magnetic disk (QMD) with a magnetic storage density of 65 Gbit/in.^{2}, over two orders of magnitude greater than the state-of-the-art magnetic storage density, has been fabricated. The planar QMD structure consists of single-domain nickel (magnetic) nanopillars uniformly embedded in a SiO_2 (nonmagnetic) disk. Electron beam lithography was used to define the QMD bit's size and location, and reactive ion etching was used to form an SiO_2 template. Nickel electroplating was used to selectively deposit nickel into the template openings, and chemical mechanical polishing was used to planarize the surface. The resulting QMD consists of ultrahigh density arrays of single-domain magnetic pillars with a 50 nm diameter and 100 nm period uniformly embedded in 200-nm-thick SiO_2 and with a surface roughness of 0.5 nm root mean square. Each single-domain structure has a quantized magnetic moment and acts as a single bit to store one bit of binary information. Furthermore, a method for mass production of QMDs, the nanoimprint technique, is discussed. © *1995 American Vacuum Society.*

I. INTRODUCTION

In a quantum magnetic disk (QMD) each bit is represented by a prepatterned nanoscale single-domain magnetic pillar or bar that was uniformly embedded in a nonmagnetic material on a disk as shown in Fig. 1. Although many QMD embodiments are possible, the particular QMD structure we report here consists of ultrahigh density arrays of nanoscale single-domain nickel pillars embedded in a SiO_2 film with an extremely smooth top surface. The size and shape of each magnetic bit is well controlled during the fabrication to ensure single-domain formation. Due to its large shape anisotropy and nanoscale size, each bit has a magnetization that is quantized along the long axis and has only two stable states: equal in magnitude but opposite in direction. Compared to ordinary magnetic disks, the QMD offers many unique advantages in writing, reading, and tracking.

Previously, we have demonstrated that nanoscale nickel structures are single magnetic domains, and that the switching field of such single-domain nickel bars can be engineered by controlling their geometric factors such as size and aspect ratio.[1] We have also developed an electroplating process for fabricating nanoscale magnetic structures.[2] In this article, we will present a QMD fabrication process which involves electron beam lithography, reactive ion etching, and chemical mechanical polishing. The fabrication process results in a QMD which consists of single-domain nickel pillars with a 50 nm diameter and 100 nm period embedded in 200 nm SiO_2 with an extremely smooth top surface with a roughness of 0.5 nm root mean square (rms). A very smooth surface is required by magnetic disk drives due to the low flying height used by magnetic recording heads. We will report the analysis of the QMD using scanning electron microscopy, atomic force microscopy, and magnetic force microscopy. Finally, we will present a low-cost process for mass producing QMD, called the nanoimprint technique.

II. PLANAR QUANTUM MAGNETIC DISK FABRICATION

The QMD fabrication process is schematically shown in Fig. 2. The fabrication process begins with a silicon substrate and the electron beam evaporation of a thin plating base of 10 nm of titanium and 50 nm of gold and an etch stop layer of 10 nm of chrome. Next, 200 nm of SiO_2 is deposited on the substrate by plasma-enhanced chemical vapor deposition (PECVD) as the nonmagnetic material that separates the bits. Then another 25 nm of chrome is deposited to be used as a dry etch mask. Finally, 70-nm-thick 950 K polymethylmethacrylate (PMMA) was spun onto the substrate.

A high resolution electron beam lithography system was used to expose dot arrays in the resist. The system used a modified JEOL 840A scanning electron microscope with a beam diameter of 4 nm. The dot arrays had periods varying from 50 nm to 1 μm and diameters varying from 35 to 100 nm. The PMMA was developed in cellosolve:methanol (3:7), and the dot array patterns were transferred into the underlying chrome layer through a wet etch. The PMMA was then

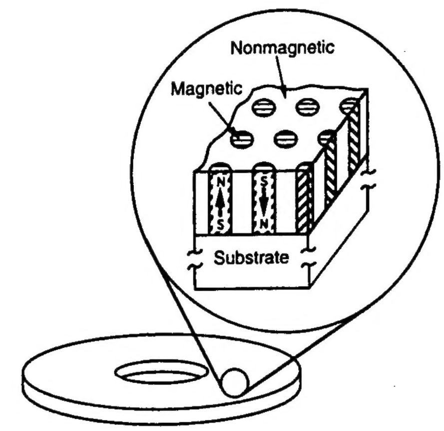

FIG. 1. Schematic of a QMD. Only the perpendicular magnetization is shown, but the disk can also be made with longitudinal magnetization.

Nanolithographically defined magnetic structures and quantum magnetic disk (invited)

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Ref-7

Isolated and interactive arrays of magnetic nanostructures as small as 15 nm are fabricated using nanolithography and related technologies, and are characterized using magnetic force microscopy. It has been demonstrated that manipulating the size, aspect ratio, and spacing of these nanostructures can lead to unique control of their magnetic properties. A quantum magnetic disk based on discrete single-domain nanomagnetic structures with storage density of 65 Gbits/in.^{2} is demonstrated along with a low-cost method for mass producing such disks. Other impacts that nanofabrication can bring to the development of future magnetic storage are discussed. © *1996 American Institute of Physics.* [S0021-8979(96)41908-8]

I. INTRODUCTION

In the epic of information and multimedia, there are increasing demands for magnetic storage devices with higher density, faster speed, lower power consumption, smaller size, and lower weight than the current state-of-the-art devices. Presently, most magnetic storage devices are based on the properties of magnetic thin films. Therefore, enormous research efforts have been devoted to the study and control of the key factors that affect magnetic thin film properties.[1–4] These factors include the size and shape anisotropy of the grains in the film, the grain magnetization orientation, the spacing and coupling between the grains, and material compositions.

The advent of nanofabrication technology opens up new avenues to manipulate magnetic materials, thereby leading to unique opportunities in developing innovative ultrahigh density magnetic storage, engineering new magnetic materials and devices, and obtaining better understanding of micromagnetics. Nanofabrication can make magnetic structures with dimensions comparable to or smaller than some fundamental length scales in magnetics, such as domain wall size and exchange interaction length, thus making the behavior different from that of a thin film. Nanofabrication can create arrays of interactive magnetic nanoparticles with precisely controlled interparticle spacing. Nanofabrication can arrange the orientation and position of the nanoparticles at one's will. With such unique manipulation ability offered by nanotechnology, many revolutionary device concepts are no longer regarded as "wild dreams," but become reality.

This article reviews research on nanomagnetic structures fabricated using electron-beam lithography and other fabrication technologies carried out at the NanoStructure Laboratory at the University of Minnesota. Particularly, this article will discuss (1) fabrication and characterization of isolated and interactive single-domain magnetic nanostructures such as bars, pillars, and rings, and (2) properties and low-cost fabrication of a 65 Gbits/in.^{2} quantum magnetic disk—a new paradigm for ultrahigh density magnetic recording media with a recording density two orders of magnitude greater than current state-of-the-art disks. The work done elsewhere on lithographically defined magnetic structures can be found in Refs. 5–8.

II. FABRICATION OF MAGNETIC STRUCTURES USING NANOLITHOGRAPHY

A typical fabrication process is illustrated in Fig. 1. In the fabrication, a resist film, polymethylmethacrylate (PMMA), is first spun onto a substrate, typically silicon. A high resolution electron beam lithography system is used to expose patterns in the PMMA.[9] The exposed PMMA is developed in a cellosolve and methanol solution to form a resist template on the substrate. Ferromagnetic materials can be patterned using either a lift-off or electroplating process. In a lift-off process, a ferromagnetic metal film is first deposited onto the entire sample. The sample is then immersed in acetone that dissolves the PMMA template and lifts off the metal on the PMMA surface, but not the metal on the substrate. In an electroplating process, a thin metal plating base is placed between the PMMA and the substrate, and the PMMA template is removed after plating. Besides use for lift-off and plating, the PMMA template also can be used to etch nanostructures into the substrate that will be used later to create magnetic nanostructures.

Figures 2–4 show scanning electron microscope (SEM) images of three magnetic nanostructures fabricated using nanolithography and a lift-off process.[10,11] The nanostructures are a high aspect ratio, isolated Ni bar 15 nm wide and 1 μm long, an interactive Ni bar array of 20 nm wide and 200 nm long bars, and Ni rings with a 90 nm mean diameter

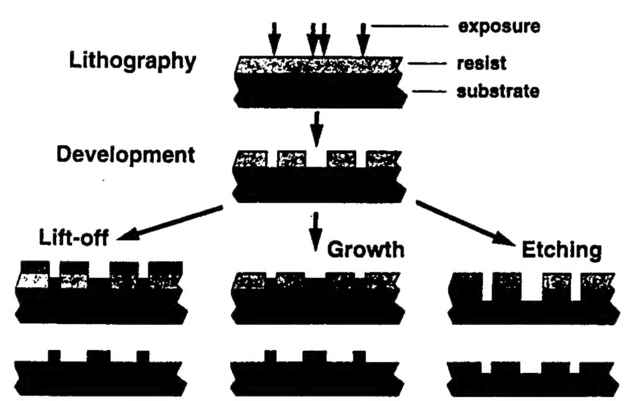

FIG. 1. Schematic of a typical process for fabricating nanomagnetic structures using nanolithography and related technologies.

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Quantum magnetic disk

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Abstract

A quantum magnetic disk (QMD) – a new paradigm for magnetic recording – is proposed and fabricated. The QMD consists of pre-fabricated single-domain magnetic structures that have an identical shape and are uniformly embedded in a nonmagnetic disk. Each single-domain structure has a quantized magnetic moment and can store one bit of information. The QMD has a number of advantages over the conventional disk and is suitable for ultra-high density recording. Two processes based on electron beam nanolithography and other nanofabrication technologies have been developed to fabricate QMDs. QMDs with a density of 65 Gbits/in^2 – over two orders of magnitude greater than the state-of-the-art magnetic storage density – have been demonstrated. A method for mass production of QMD without employing lithography is discussed.

1. Introduction

In a conventional magnetic disk (CMD), a writing head must simultaneously define the location, shape, and magnetization moment of each bit. A slight error in doing so could lead to errors in reading the bit and neighboring bits. The bits on CMDs are stored in a continuous thin magnetic film. Often, there are no recognizable boundaries between bits, making their reading and writing 'blind' and dependent solely upon the mechanical accuracy of the drive. The continuous film also can exhibit cross-talking in high density storage, namely the switching of one bit will automatically switch a neighboring bit due to the exchange force.

Naturally, one could ask whether it would not be better if the writing head did not need to define the location, shape and magnetization moment of each bit? Wouldn't it be better if the disk drive could see each bit before reading and writing it? Wouldn't it be better if the exchange force between the bits and hence the cross-talk could be reduced? The quantum magnetic disk (QMD) – a new paradigm for ultrahigh density magnetic disk that we proposed here – is a major step in this direction [1].

2. Quantum magnetic disks

A QMD consists of pre-fabricated single-domain magnetic structures (e.g. array of bars or pillars) that have an identical shape and are uniformly embedded in a nonmagnetic disk, as shown in Fig. 1. The magnetic moment of each single-domain structure has only two quantized states: the same in magnitude but opposite in direction. Therefore, each single-domain structure can store one binary bit of information.

QMDs have a number of advantages over CMDs making them suitable for ultra-high density storage as shown in Fig. 2. First, the writing process in QMD is greatly simplified. Unlike CMDs where the writing process must define the location, shape, and magnetization moment of a bit, the writing process in QMD just simply flips the quantized magnetization orientation of a pre-patterned sin-

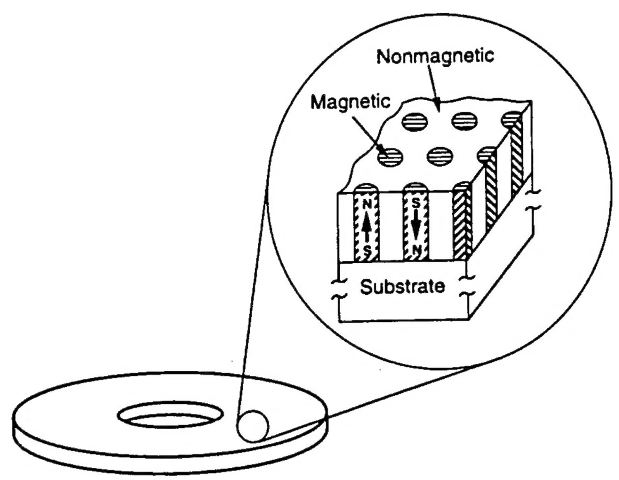

Fig. 1. Schematic of a QMD. Only the vertical magnetization is shown, but the disk can also be made with longitudinal magnetization.

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Effects of bar length on switching field of nanoscale nickel and cobalt bars fabricated using lithography

Ref - 9

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The switching behavior of isolated nanoscale nickel and cobalt bars, which were fabricated using electron-beam lithography, was studied as a function of bar length. The bars have a 35 nm thickness, a 100 nm width, and a length varying from 200 nm to 5 μm. Magnetic force microscopy showed that except for the Ni bars with a length equal to or less than 250 nm, all other as-fabricated bars were single domain. Unlike the bar width dependence, the switching field of the single-domain bars was found to first increase with the bar length, then decrease after reaching a peak. The peak switching field and the corresponding bar length are 640 Oe and 1 μm for Ni and 1250 Oe and 2 μm for Co, respectively. The nonmonotonic length dependence suggests that the magnetization switching may be quasicoherent in the short bars and incoherent in the long bars, and that the exchange coupling is much stronger in Co bars than in Ni bars. Furthermore, the switching field of 1-μm-long Co bars was found to increase monotonically as the bar width decreases, reaching 3000 Oe at a 30 nm width. © *1996 American Institute of Physics.* [S0021-8979(96)02121-4]

I. INTRODUCTION

Magnetic particles are of great interest to magnetic recording.[1–4] With the advancement of nanofabrication technology, it is possible to fabricate magnetic bars which are single domain but have dimensions much larger than those of the single-domain particles studied before. Understanding these lithographically patterned magnetic bars is important in developing ultrahigh-density magnetic recording media, such as quantum magnetic disks that consist of discrete single-domain bits.[5] Previously, the effects of bar width on the switching field of lithographically patterned NiFe and Ni bars have been studied.[6,7] In this article we present the effects of bar length on the switching field of nanoscale Ni and Co bars fabricated using e-beam lithography. We have observed that, unlike the width dependence found previously, the switching field of single domain bars nonmonotonically depends on the bar length.

II. FABRICATION AND MEASUREMENTS

The isolated Ni and Co bars were fabricated using e-beam lithography and a lift-off technique. In the fabrication, rectangular patterns were exposed in a thin film of polymethyl methacrylate (PMMA) on a silicon substrate with high-resolution e-beam lithography. The exposed PMMA was removed in development, resulting in rectangular trenches in the PMMA. Then Ni or Co was evaporated onto the entire sample. Finally, the sample was immersed in acetone which dissolved the PMMA template and lifted off the metal on the PMMA surface, leaving isolated metal bars on the substrate. The details of the fabrication have been published elsewhere.[7,8] Both Ni and Co bars have a thickness of 35 nm and a width of 100 nm, but the length of Ni bars varies from 250 nm to 5 μm and the Co bars from 200 nm to 5 μm. Figure 1 shows a scanning electron micrograph (SEM) of a typical 1-μm-long and 100-nm-wide Ni bar.

From x-ray diffraction, the as-deposited Co thin film is found to be polycrystalline and have a hexagonal crystal structure. The initial magnetization states and the switching behavior of the Ni and Co bars were observed using a commercial scanning magnetic force microscope (MFM) with a ultrahigh-resolution tip made in-house. The topological and magnetic images were taken at the same time. In the study of the switching behavior of the single domain bars, the magnetization states of the bars were observed using the MFM first. Then the sample was taken out from the MFM and placed in a magnetic field applied in the direction opposite to the bar's original magnetization. Finally, the sample was put back into the MFM for further examination. This process continued and the applied field was gradually increased until the magnetization of the bar reversed. That field is defined as the switching field of the bar. The accuracy of this measurement is typically 10 Oe. Furthermore, due to fabrication inhomogeneity, there is a slight variation of the switching field

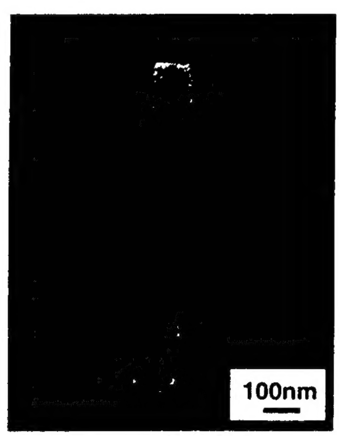

FIG. 1. Scanning electron micrograph of a Ni bar that is 1 μm long, 100 nm wide, and 35 nm thick.

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